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Load Balancing Metric with Diversity for Energy Efficient Routing in Wireless Sensor Networks

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Abstract

The expected number of transmission (ETX) represents a routing metric that considers the highly variable link qualities for a specific radio in Wireless Sensor Networks (WSNs). To adapt to these differences, radio diversity is a recently explored solution for WSNs. In this paper, we propose an energy balancing metric which explores the diversity in link qualities present at different radios. The goal is to effectively use the energy of the network and therefore extend the network lifetime. The proposed metric takes into account the transmission and reception costs for a specific radio in order to choose an energy efficient radio. In addition, the metric uses the remaining energy of nodes in order to regulate the traffic so that critical nodes are avoided. We show by simulations that our metric can improve the network lifetime up to 20%.

Keywords: Wireless sensor networks, network lifetime, load balancing, ETX, routing protocols.

1. Introduction

Energy-efficiency is a critical issue in wireless sensor networks (WSNs) due to the limited capacity of the sensor nodes's batteries [1]. This limited energy capacity dictates how the communication must be performed inside WSNs. WSN protocols must make judicious use of the finite-energy resources. Typically, sensor nodes avoid direct communication with a distant destination since a high transmission power is needed to achieve a reliable transmission [2]. Instead, sensor nodes communicate by forming a multi-hop network to forward messages to the sink node, which is also called the Base Station (BS). In addition to using multi-hop communications, an efficient routing protocol becomes crucial to extend the network lifetime, which refers to the period of time from the deployment of the sensor nodes to the instant when the network is considered unusable [3].

This requires sensors to be able to self-organize and self-configure in order to adapt to the environment and reduce the energy consumption. Radio link qualities are time and location dependent, which vary with the environmental characteristics [4]. Transmitting a packet over a specific radio link has a direct effect on the energy consumption. Sending a packet over a bad link requires more packet retransmission until the successful transmission. In [4], the authors explored the diversity in link qualities, present at each radio, in order to improve reliability at the cost of increase in energy. In this paper, we propose an energy balancing metric for diversity. The goal is to improve the energy consumption by avoiding bad links which cause an overhead in energy consumption due to the packets retransmission. In addition, in order to use effectively the energy present in the network, we propose a new metric for routing to make a balance of the energy consumption over the network, and we show how the network lifetime is extended up to 20%.

The rest of the paper is organized as follows. Section 2 investigates the related work. Section 3 investigates the system model, while Section 4 shows the proposed strategies. Section 5 investigates performance evaluations and we conclude in Section 6.

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2. Related work

Multi-radios systems have been intensively studied in recent year due to their ability to increase the performance of a network [5]. The use of multiple radios in data communication systems is a common technique refereed to as Multiple Input Multiple Output (*MIMO*) and many metrics have been proposed to enhance the routing performance. An interesting survey for routing metric in wireless mesh networks can be found in [6]. We review some of them in what follows, which are related to our work.

The Weighted Cumulative Expected Transmission Time (*WCETT*) routing metric [7] was designed specifically for multi-radio multi-channel wireless networks. It calculates the Expected Transmission Time (*ETT*) of each hop and makes the routing decision based on the Cumulative *ETT* (*CETT*) and the channel diversity of each candidate route, which is characterized indirectly by the sum of *ETT*s of hops operating at the Bottleneck frequency channel (*BETT*). The tradeoff between *CETT* and *BETT* is indicated by a weight β :

$$WCETT = (1 - \beta) \times CETT + \beta \times BETT \quad (1)$$

The Metric of Interference and Channel switching cost (*MIC*) was designed to support load-balanced routing and to consider intra-flow and inter-flow interference, in addition to being isotonic [3]. The metric for a path p is defined as follows:

$$MIC(p) = \alpha \times \sum_{l \in p} IRU_l + \sum_{l \in p} CSC_i \quad (2)$$

where p represents a path in the network, l is a link in p , and the parameter i is a node in the path, and α is a tunable parameter that allows to vary the weight given to the two components of *MIC*. The first component, *IRU*, considers inter-flow interference, while the second component, *CSC*, represents the level of intra-flow interference. The prior metric are designed for mesh networks and there is no consideration of energy consumption to save the energy.

Recently, the authors in [4] proposed a multi-radio scheme for WSNs. They explored the diversity in *ETX* [8] metric present in each radio in order to improve the reliability performance at the cost of increase in energy.

Our proposed scheme is different from the prior existing architectures as it uses a novel metric related to both the link quality and the energy cost to make a decision when routing. Indeed, we propose a load balancing metric to extend the network lifetime. To our best of knowledge, we are the first proposing an energy efficient load balancing metric for routing in multi-radio WSNs.

3. System model

We assume a WSN consists of N sensors deployed in a field to continuously monitor an environment. We denote the i -th sensor node by n_i and the corresponding set of sensor nodes $S = \{n_1, n_2, \dots, n_N\}$ where $|S| = N$. We make the following assumptions about sensor nodes and the network:

- Sensor nodes and the BS are all stationary after the deployment.
- Nodes in Single Input Single Output (*SISO*) are equipped with a single radio r_1 or r_2 , while nodes in the *MIMO* are equipped with multiple radios (in our case r_1 and r_2). We denote $E_{r_1}^{tx}$, $E_{r_2}^{tx}$ the energy of transmitting a packet for r_1 and r_2 , respectively. Similarly, we denote $E_{r_1}^{rx}$, $E_{r_2}^{rx}$ the energy of reception a packet by r_1 and r_2 , respectively.
- We denote the set of n_i neighbors by Ne_i . Each node n_i can reach its neighbor n_j ($n_j \in Ne_i$) with $E_{r_1}^{tx}$ or $E_{r_2}^{tx}$ for r_1 and r_2 , respectively.
- Links are symmetric [9], i.e., if $n_i \in Ne_j$, then $n_j \in Ne_i$. Links are not perfect and they are characterized by a *PRR* (packet reception ratio), which reflects the link quality. The *PRR* is defined as the probability of a packet reception over a link. We assume that the *PRR* during the deployment

is constant. We denote PRR_{r_1} and PRR_{r_2} the PRR of links for r_1 and r_2 , respectively. We assume that the PRR of the link is symmetric. If n_i have a PRR $PRR_{r_1}(l)$ to its neighbor $n_j \in Ne_i$, then n_j have also the same $PRR_{r_1}(l)$ to its $n_i \in Ne_j$ using r_1 .

- Nodes use a collection tree protocol to send data toward a BS according to some routing metric. The metric in *SISO* mode is the $ETX = \frac{1}{PRR}$ metric. The ETX [8] metric represents the expected number of transmission a node needs in order to successfully deliver a packet. It is to be noted that the state-of-the-art Collection Tree Protocol (CTP) [10] uses ETX to forward data.
- Nodes use infinite retransmissions to improve their packet delivery rate to the BS.

The objective of our proposed protocol is to use effectively the energy of the network and therefore extend the network lifetime.

4. Proposed load balancing metric

Having multiple radios on a node enables it to choose the radio with the least cost when forwarding a packet [4]. The ETX metric used in [4] is defined as follows.

$$ETX(i, j) = \min(ETX_{r_k}(i, j)) \quad (3)$$

where $k = 1, 2$, $i, j \leq N$, and ETX_{r_k} is the expected number of transmission over a radio r_k . We call R^{ETX} the routing protocol using the ETX metric as shown in equation (3). R^{ETX} chooses the radio that has the least number expected of transmission to a neighbor at the two radios. The goal is to improve the reliability of the network but at the increase in energy consumption. Indeed, R^{ETX} may choose the best link in PRR but with the highest energy consumption.

Based on (3), to minimize the energy consumption the Weighted ETX ($WETX$) is considered when making routing decisions, as shown in what follows.

$$WETX(i, j) = \min(E_{r_k}^{tx} \times ETX_{r_k}(i, j) + E_{r_k}^{rx}) \quad (4)$$

where $k = 1, 2$, $i, j \leq N$, and $n_i \in Ne_j$. For a link (i, j) , $WETX(i, j)$ reflects the expected energy consumed when transmitting a packet over this link. We call R^{WETX} the routing protocol using $WETX$ metric. In contrary to R^{ETX} , R^{WETX} combines the transmission and reception costs of the radios with the ETX . At each node, R^{WETX} chooses the radio that has the minimum $WETX$ metric. Then, it uses this metric to select the next-hop node that minimizes the sum of $WETX$ along the path to the final destination.

Based on (4), we propose a novel metric BL (for balancing) that enables nodes to balance the energy consumption over the network. Indeed, we weight the $WETX$ metric with the residual energy of node's neighborhood as follows.

$$BL(i, j) = \frac{WETX(i, j)}{RE_j} \quad (5)$$

where $i, j \leq N$, RE_j is the remaining energy of the node n_j , $n_i \in Ne_j$, and $WETX(i, j)$ is the cost obtained in the equation (4). We call this strategy R^{BL} . The goal of R^{BL} is to regulate the traffic over the network by avoiding the overload of nodes. We summarize in Tab. 4 the name of the different strategies and their meaning.

To illustrate the different strategies and the motivation behind our proposition let us consider the following example.

4.1. Example

In this example we consider a simple topology presented in Fig. 3(a), which shows the PRR of links in the two radios r_1 and r_2 . For illustration, we consider $(E_{tx}^{r_1}, E_{rx}^{r_1}) = (4, 1)$ energy unit, $(E_{tx}^{r_2}, E_{rx}^{r_2}) = (1, 1)$ energy unit. We also consider a free energy consumption at the BS as it is not energy constrained.

Table 1 Routing strategies.

| Name | Description |
|------------|--|
| R_{r_i} | Routing using <i>SISO</i> on $r_i, i = 1, 2$. |
| R^{ETX} | Routing using <i>MIMO</i> with the <i>ETX</i> metric. |
| R^{WETX} | Routing using <i>MIMO</i> with the <i>WETX</i> metric. |
| R^{BL} | Routing using <i>MIMO</i> with the <i>BL</i> metric. |

We denote *WETX* and *ETX* the $N \times N$ matrices of cost used to forward packets when using R^{WETX} and R^{ETX} , respectively, where the $WETX(i, j)$ and $ETX(i, j)$ costs are calculated following the equations shown in (4) and (3), respectively. From the *PRR* shown in the Fig. 3(a) we obtain the following.

$$ETX = \begin{pmatrix} - & \frac{1}{0.2} = 5 & 5.26 & - \\ 5 & - & - & 1.26 \\ 5.26 & - & - & 1.26 \\ - & 1.26 & 1.26 & - \end{pmatrix}, WETX = \begin{pmatrix} - & 1 \times \frac{1}{0.1} + 1 = 11 & 7.66 & - \\ 11 & - & - & 1.26 \\ 7.66 & - & - & 1.26 \\ - & 1.26 & 1.26 & - \end{pmatrix}$$

Recall that *WETX* and *ETX* represent the cost matrices. These costs are used to find the minimum cost path, with using Dijkstra algorithm, when forwarding the packets toward the BS. Therefore, to send the packet from n_4 to n_1 , R^{ETX} chooses the path of $n_1 \rightarrow n_2 \rightarrow n_4$ with using radios $r_1 \rightarrow r_2$, which corresponds to the total cost of $5 + 1.26 = 6.26$. However R^{WETX} chooses the path of $n_1 \rightarrow n_3 \rightarrow n_4$ with using the radios $r_2 \rightarrow r_2$, which corresponds to the total cost of 8.92.

It is important to notice that even though the *WETX* metric uses minimum energy to forward packets, it does not balance the traffic over the network. Indeed, the path used will be every time $n_1 \rightarrow n_3 \rightarrow n_4$. In such a situation the energy of the node n_3 will be drained. Therefore the motivation of R^{BL} scheme is to take the advantage of choosing an energy efficient radio for each link, while it keeps updating the cost *WETX* by the remaining energy of nodes. The rationale behind dividing the cost $WETX(i, j)$ by $\frac{1}{RE_j}$ is to increase the cost of nodes with small residual energy, so that R^{BL} will regulate the traffic and therefore avoid forwarding packets to nodes with small residual energy. By doing so, R^{BL} will use both the paths $n_1 \rightarrow n_3 \rightarrow n_4$ and $n_1 \rightarrow n_2 \rightarrow n_4$ to deliver the packets.

5. Simulation results

To evaluate the performance of the different schemes, we build an event driven simulator with Matlab, which simulates the different routing strategies.

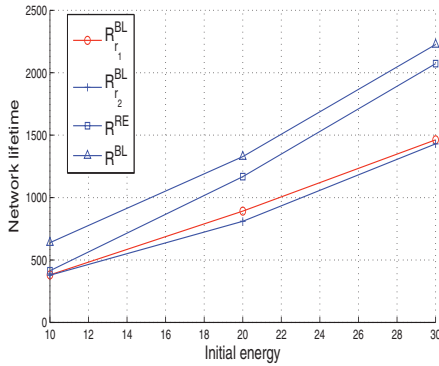
We consider a continuous monitoring application in which data are generated periodically at a predefined period P . We consider an illustrative network presented in Fig. 3(b), where we consider n_{16} to be the source and n_1 to be the BS and both of them are free energy consumption. Note that the following results are averaged for 20 simulation runs and for each run we use different seeds for the random *PRR* generation. The parameters used in simulation are shown in the table 5.

Fig. 1(a) shows the network lifetime, defined as when the first node dies, with varying the initial energy. We call $R_{r_k}^{BL}$ the routing scheme with R_{r_k} and with using the metric cost $\frac{ETX_{r_k}(i,j)}{RE_j}$ for packets forwarding, where $k = 1, 2$ and $n_i \in Ne_j$ and $i, j \leq N$. We also call R^{RE} the routing that uses the metric cost $\frac{1}{RE_j}$ for packets forwarding, while it keeps using the *WETX* metric for radios selection. The main difference between R^{RE} and R^{BL} is that they use different costs for packets forwarding (i.e., R^{RE} and R^{BL} use the costs $\frac{1}{RE_j}$ and *BL*, respectively). We observe from Fig. 1(a) that R^{BL} achieves an improvement in network lifetime of 7% compared to R^{RE} and an improvement of 36% compared to both $R_{r_1}^{BL}$ and $R_{r_2}^{BL}$. Indeed, using only one radio for routing, as in $R_{r_1}^{BL}$ and $R_{r_2}^{BL}$, is not suitable due to the differences in *PRR* that

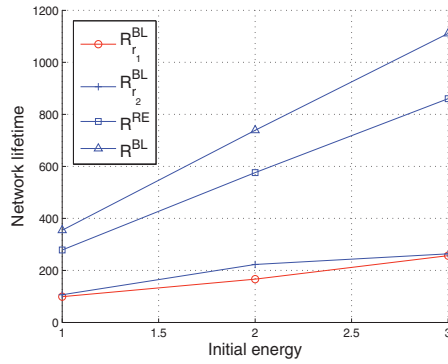
Table 2 Simulation Parameters.

| Parameter | Meaning | Value |
|----------------|--|-----------------|
| E_{ini} | Initial energy of nodes | Variable |
| $E_{r_1}^{tx}$ | Energy cost of transmission with r_1 | 1 energy unit |
| $E_{r_2}^{tx}$ | Energy cost of transmission with r_2 | 1 energy unit |
| $E_{r_1}^{rx}$ | Energy cost of reception with r_1 | 0.1 energy unit |
| $E_{r_2}^{rx}$ | Energy cost of reception with r_2 | 0.1 energy unit |
| TT | Packet transmission duration | 2 time unit |
| TR | Retransmission time out | 2.5 time unit |
| P | Period of data generation | 10 time unit |

can be present in radios. In addition, with using two radios, focusing only on the residual energy to forward packets as in R^{RE} is not suitable due to the fact that it can choose a link that can use quickly the energy of nodes.



(a) Full network of 16 nodes.



(b) Grid network of 16 nodes.

Figure 1: Network lifetime Vs initial energy.

Fig. 2(a) and Fig. 2(b) show the residual energy of nodes when the first node dies in R^{WETX} and R^{BL} , respectively. As expected, we observe in Fig. 2(b) that R^{WETX} uses only one path $n_1 \rightarrow n_{12} \rightarrow n_{16}$, while we observe in Fig. 2(a) that R^{BL} utilizes all the possible paths from the source n_{16} to the BS. In this scenario, the nodes which first drain their energy are n_{13} and n_{12} in case of R^{BL} and R^{WETX} , respectively. The energy utilization is $\eta = 89.05\%$ and $\eta = 7.1\%$ for R^{BL} and R^{WETX} , respectively. The two scenarios explain that R^{BL} uses effectively the energy of the network to achieve a longer network lifetime compared to R^{WETX} .

To validate our results, in a more realistic setting, we build an energy consumption model characterizing the energy consumption of our hardware platform *Opal* [4] supporting two radios r_1 and r_2 for *RF230* [11] and *RF212* [12], respectively.

The transmission and reception energy costs depend on the underlying low power listening layer (*LPL*).

We derive hereafter the energy consumption by considering the *LPL* [13], [14]. We denote the average energy consumption when a packet is transmitted successfully, when the packet is failed, and when the packet is received for r_i by $E_{r_i}^{stx}$, $E_{r_i}^{ftx}$, and $E_{r_i}^{rx}$, $i = 1, 2$, respectively.

$$E_{r_i}^{stx} = (LPL/2 \times I_{r_i}^{tx} + delay \times I_{r_i}^{rx}) \times V \quad (6)$$

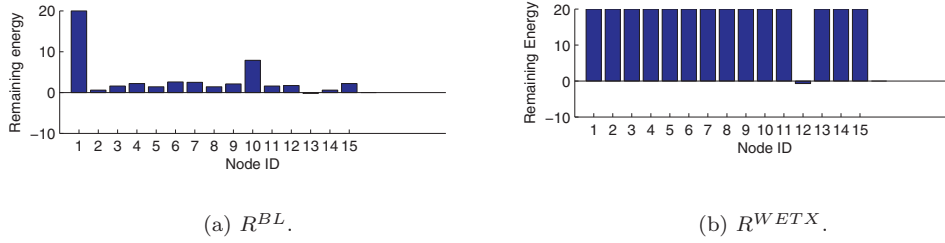


Figure 2: Residual energy of nodes at the network lifetime.

$$E_{r_i}^{ftx} = LPL \times I_{r_i}^{tx} \times V \quad (7)$$

$$E_{r_i}^{rx} = (sample/2 + delay) \times I_{r_i}^{rx} \times V \quad (8)$$

Based on equations (6) and (7), the average energy consumed when transmitting a packet over a link with $PRR_{r_i}(l)$ is

$$E_{r_i}^{tx}(l) = E_{r_i}^{ftx} \times \left(\frac{1}{PRR_{r_i}(l)} - 1 \right) + E_{r_i}^{stx} + E_{r_i}^{rx}, i = 1, 2 \quad (9)$$

where LPL is the low power listening interval at a receiver node, $I_{r_i}^{tx}$ is the radios current draw when transmitting, $I_{r_i}^{rx}$ is the radios current draw when receiving, V is the voltage, $sample$ is the time it takes for a node to check the channel for activity, and $delay$ is a constant time in which the radio is kept on after reception or transmission.

The parameters used in this section are those of *Opal* supporting two radios *RF212* and *RF230* (see Tab. 5).

Table 3 Hardware characteristics.

| Parameter | Meaning | Value |
|----------------|------------------------------------|----------|
| $delay$ | Delay constant | 20ms |
| $sample$ | Sampling check time | 50ms |
| LPL | Low Power Interval | Variable |
| $I_{r_1}^{tx}$ | Current of transmission with r_1 | 24mA |
| $I_{r_2}^{tx}$ | Current of transmission with r_2 | 16mA |
| $I_{r_1}^{rx}$ | Current of reception with r_1 | 9mA |
| $I_{r_2}^{rx}$ | Current of reception with r_2 | 15mA |

We used the grid topology of 4×4 similar to that of our testbed (see Fig.3(c)). Here only n_{16} is generating packet. Note that the following results are averaged for 20 simulation runs and for each run we use different seeds for the random PRR generation.

Fig. 1(b) shows the network lifetime with initial energy. As expected, the results show that R^{BL} achieves a longer network lifetime compared to $R_{r_1}^{BL}$, $R_{r_2}^{BL}$, and R^{RE} as it regulates the traffic and uses effectively the energy of the network.

Fig. 4(a), Fig. 4(b) and Fig. 4(c) show the network lifetime with varying the LPL interval. The rationale behind that is to analyze how the increases in energy consumption, due to the variation in the LPL interval, will affect the network lifetime. Note that in this scenarios all the nodes are involved in the periodic data reporting.

Fig. 4(a) shows the network lifetime when the LPL interval is the same for the two radios ($LPL = 500ms$). As expected, we observe that R^{BL} achieves a longer lifetime compared to (R^{ETX} , R^{WETX}), which performs similarly in this scenario, and compared to (R_{r_1} , R_{r_2}). The similarity observed between R^{WETX} and R^{ETX} is due to the fact that R^{WETX} and R^{ETX} tend to use the same radio links to forward the

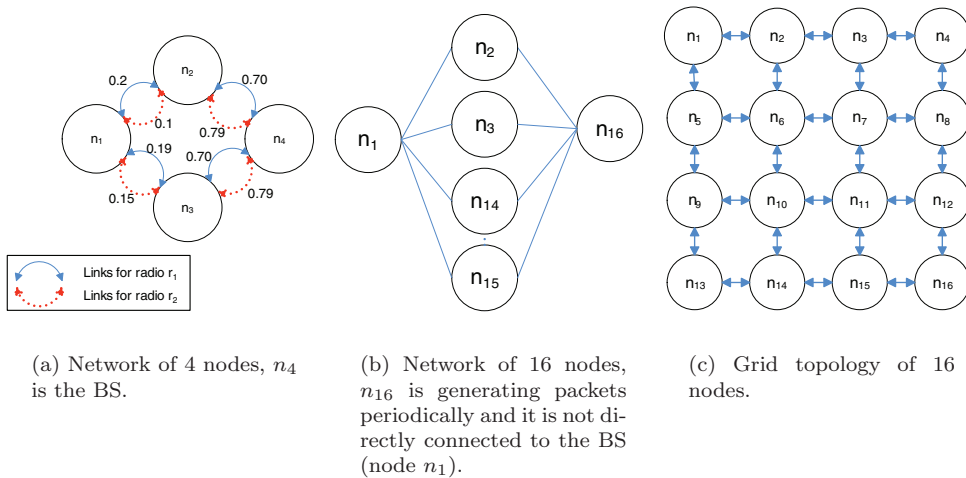
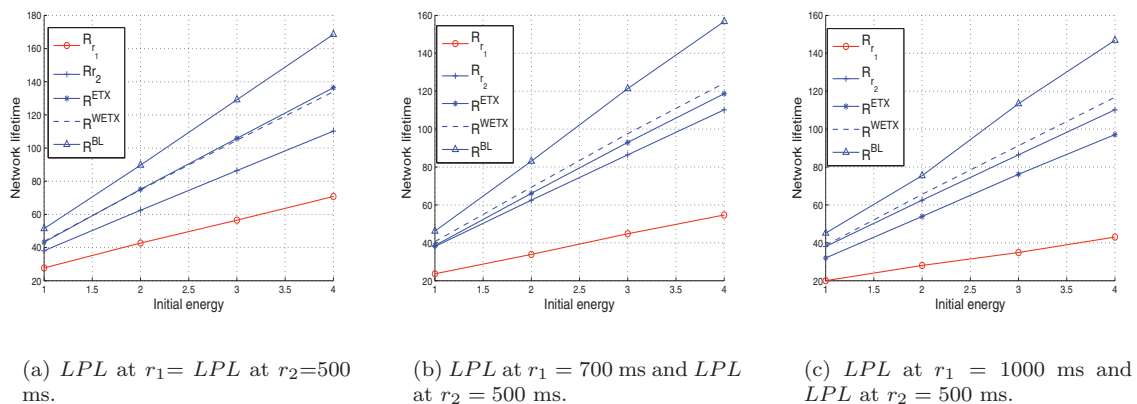


Figure 3: Network topologies.

packets. The improvement observed in the network lifetime is up to 58% compared to the single radio (i.e., R_{r_1}) and 20% compared to multiple radios (i.e., R^{ETX} and R^{WETX}).

Fig. 4(b) and Fig. 4(c) shows the lifetime with increasing the LPL of r_1 to 700 ms and 1000 ms, respectively. As expected, R^{BL} still performs better than R^{ETX} , R^{WETX} , R_{r_1} , and R_{r_2} . From the figures, we observe that R^{BL} achieves a lifetime improvement of 20% compared to R^{WETX} . In addition, we observe that the lifetime of R_{r_1} is getting worst with increases of the LPL at r_1 . The comparison of R^{BL} with R_{r_1} shows that R^{BL} achieves a lifetime improvement of 65% and 71% with $LPL = 700$ ms and $LPL = 1000$ ms, respectively. This can be explained by the fact of the increase in the energy consumption of nodes when using links of r_1 . Furthermore, we observe from Fig. 4(c) that R^{ETX} gets a worse lifetime compared to R^{WETX} . The comparison of R^{BL} with R^{ETX} shows that R^{BL} achieves an improvement in lifetime of 25% and 34% with $LPL = 700$ and $LPL = 1000$, respectively. That can be explained by the fact that R^{ETX} aims to improve the reliability of the network by choosing the best quality link with not regarding the energy cost of links. From Fig. 4(a), Fig. 4(b) and Fig. 4(c), we conclude that R^{BL} achieves a lifetime improvement of almost 20% compared to R^{WETX} , while the lifetime improvement is getting in increases with the increases of LPL with comparing to R^{ETX} .

Figure 4: Network lifetime with LPL .

6. Conclusions

In this paper, we investigated the benefit of using multiple radios due to the diversity of link quality present at each radio. We proposed a load balancing metric in *MIMO* model that exploits the diversity present in the radio link quality to extend the network lifetime. To evaluate the performance of our proposal, we built an event driven simulator for the different strategies that reflects the energy consumption of our real hardware nodes. The proposed energy balancing metric is compared to R^{ETX} , R^{WETX} , and R^{RE} for *MIMO* scheme and also with using only one radio. The results obtained clearly demonstrate that the proposed metric will increase the network lifetime up to 20%.

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